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SATURN

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ABSTRACT. The article is a brief and "popular" account of research to date on the rings of Saturn. Some of the findings are presented, as regards the composition of the rings, and the author seeks to end the disputes concerning their thickness.

The planet Saturn is unique in its form of embellishment -- its gigantic system of concentric flat rings -- which formerly riveted the attention of workers in planetary science, celestial mechanics, and cosmology, remaining a nearly unlimited field of investigation. At the same time the observers who were studying the disk of Saturn were inclined to view the rings more readily as a hinderance to their work, inasmuch as the rings emit a great deal of "parasitic" light and in that way obstruct a significant portion of the disk. /10*

There are, however, periods of visibility of Saturn in which these two, it would seem, irreconcilable points of view are successfully reconciled. This occurs in those years in which the expansion of the rings decreases to a minimum and the ellipse of the rings, contracting into a line, becomes similar to a needle of light, which pierces the body of Saturn at the equator. At that time a vast number of facts are collected by the observers of the rings, the observers of the disk, and also the observers of Saturn's satellites. Actually, the light flux from the rings at that time is relatively small and almost does not interfere with observations of the disk and the planet's satellites; it becomes possible for the investigators of the rings to obtain measurements of their thickness since the rings are turned toward the Earth edgewise. In certain

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*Numbers in the margin indicate pagination in the foreign text.

attitudes of Saturn, the Sun and the Earth are on different sides with respect to the thickness of the rings, and at that point the terrestrial observer is in a position to study the dark "night" side of the rings. Finally, with minimal expansions of the rings, the visible orbits of a majority of the satellites intersect the disk of Saturn and eclipses of the satellites by the disk occur, as well as their passage across the disk, which is also interesting for planetary astronomy.

Passage of the Earth Through the Plane of the Rings

For clearer understanding of what is to follow it is useful to remember that the expansion of the rings of Saturn changes periodically, inasmuch as /11 the plane of the rings during movement of the planet along its orbit changes in space in a manner parallel with respect to the rings themselves. At this point it is necessary to note that in one complete rotation of Saturn in its orbit (nearly 29 and 1/2 years), the Sun twice passes through the plane of the rings, and twice the greatest expansion of the rings occurs from the point of view of a hypothetical observer on the Sun. Since the orbit of Saturn is not exactly circular, the speed of the planet near perihelion is greater than near aphelion, and therefore the intervals between subsequent passages of the Sun through the plane of the rings are not uniform (13 3/4 and 15 3/4 years). Approximately 180 days before the time in which the plane of the rings passes through the Sun, it begins to intersect the orbit of the Earth, and after 180 days converges with it. Usually in these 360 days the Earth passes through the plane of the rings either once or three times. In the period 1936 to 1937, one passage and one very close approach of the Earth to the plane of the rings were observed (almost a state of tangency), but such cases are rare.

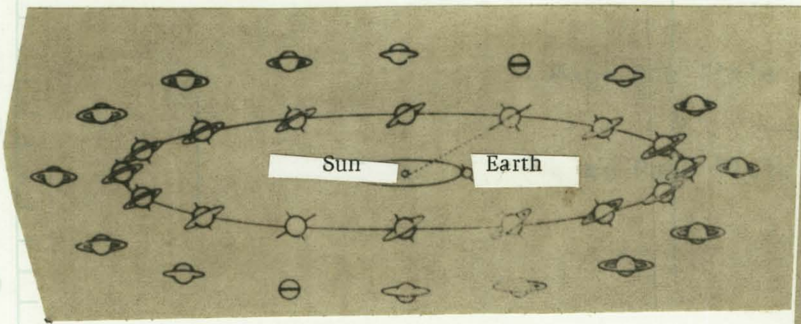
The last series of the passages, which were extremely favorable for astronomers, occurred in 1966. The Earth intersected the plane of the rings three times — in April, in October and in December. It was impossible to observe the April passage due to the nearness of Saturn to the Sun; the other two, on the other hand, were entirely suitable for observation. The Sun intercepted the plane of the rings in June, converting the southern side of the rings, which was turned toward the Earth, from "night" to "day." The second period of visibility of the "night" side continued from 29 October until 17 December, and afterwards the Earth finally moved to the southern side of the rings, where it will remain until 1980.

The World Saturn Watch of 1966

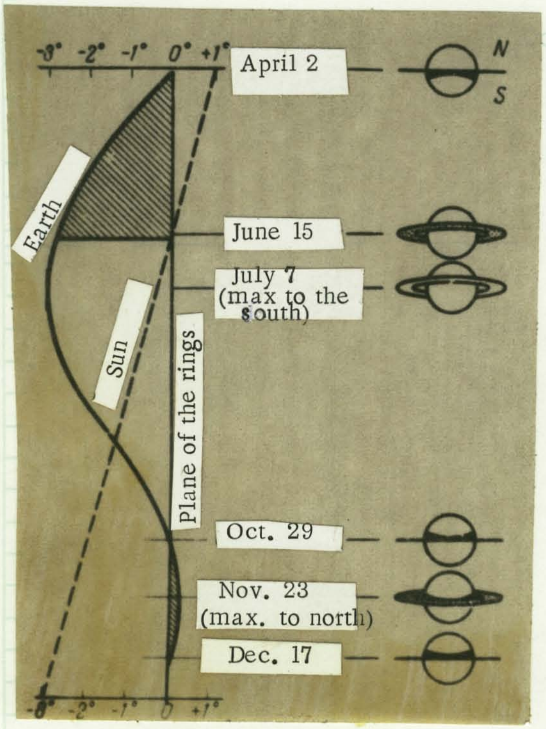
The moment of the passage of the Earth through the plane of the rings is calculated in a timely manner. But since the attitude of the plane of the rings of Saturn in space in 1966 was known with an insufficiently high degree of accuracy, a calculation of the moments of passage could contain an error of as much as one day. Therefore it could not be determined in advance for which observatories, at the moment of the October or December passages, Saturn would appear above the horizon. At the suggestion of the author of this article, the International Astronomical Union organized, in 1966, a world watch for Saturn. For a period of many days, the observatories of Europe, Asia, North America, Australia, and New Zealand followed the planet around the clock. What did these astronomers find out about Saturn?

The D-Ring. The existence of yet another — an outermost ring — outside the boundaries of the present system of the rings of Saturn has been suspected for a time beginning with the second half of the last century; however, all previous evidence was based on subjective, purely visual observations. Some observers, including extremely authoritative ones, for example, E. Barnard, all in all considered this to be a fiction. The American astronomer V. Feibelman (1966) first confirmed the existence of the D-ring objectively, having obtained its image on photographic film.

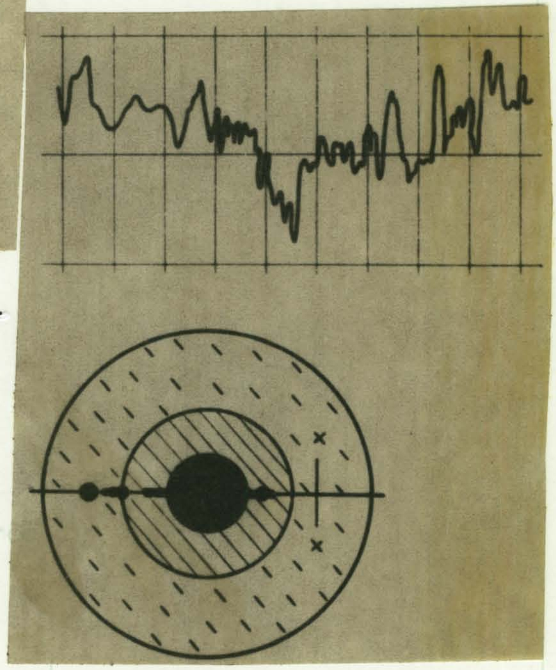
The D-ring lies in the same plane as do the rest of the rings, but is distinguished from them by extreme thinness; evidence of it is obtained in photographs only in conditions in which the Earth is located nearly in the plane of the rings, and, moreover, from the side lying opposite the Sun. The diameter of the D-ring exceeds the dimensions of the earlier known system of /12
rings by more than twice.



The Phases of the Rings of Saturn. (Drawing by C. Huygens) In one revolution of the planet along its orbit the plane of the rings passes twice through the Sun and once through the orbit of the Earth.



A View of the Rings of Saturn and Changes in the Angles of Inclination of the Earth and the Sun Over the Plane of the Rings in 1966. The shaded zones designate that the "night" side of the rings is turned toward the Earth.

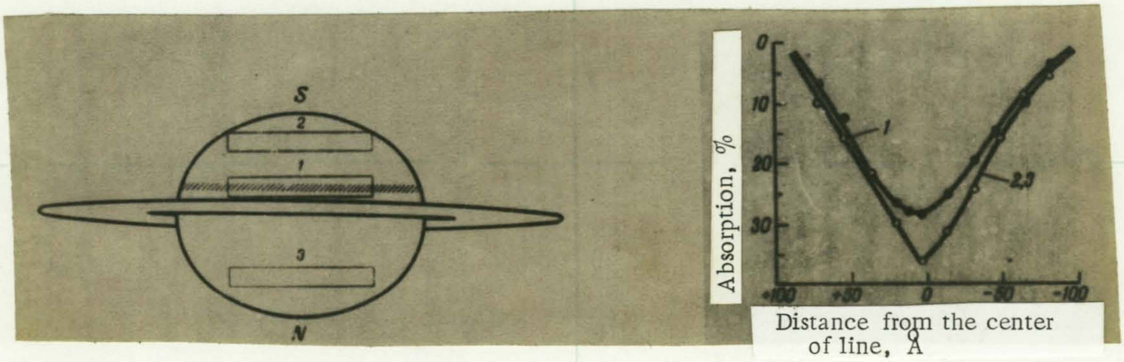


A Schematic Representation of the System of Saturn (According to a Negative Obtained by V. Feibelman on 14 November, 1966). The following are visible: the dark body of the planet, the rings from the edgewise position, and the satellites of Saturn. The internal shaded circle corresponds to the dimensions of a representation of a strongly overexposed disk of the planet; the external correspond to the dimensions of the photographic corona of the disk. The thin horizontal lines showed the trace of the D-ring. Above, a registrogram was made of the darkening of the negative along the cross-section X-X. The drop in the center was caused by the darkening from the D-ring.

The Tenth Satellite. An unexpected but extremely beneficial result of the international program of observations was the discovery of Saturn's tenth satellite. As we know, the satellite, named Janus, was discovered on 15 December 1966 by O. Dolfuss at the French, high altitude observatory at Pic du Midi [1]. Its nearness to the bright rings and its weak brightness (of the fourteenth stellar magnitude) makes this satellite an object which is extremely difficult to find. In a manner similar to that of ring D, Janus is distinguishable only in periods in which the night side of the rings are visible; additionally, at the moment of observation it must be located at the maximal visible distance from Saturn (in an eastern or western elongation).

It is curious to note that Janus, as well as the more distant satellite of Saturn, Enceladus, moves around the planet, being located at all times within the D-ring, in a resistant medium as it were, although this medium is very thin. True, the speed of the particles of the ring relative to the speed of the satellite must be near zero, since these and the others are determined by Kepler's third law for circular orbits. With respect to Mimas, the satellite which moves between Janus and Enceladus, its orbit is inclined with respect to the plane of the rings at 1° 5" and therefore it only periodically intersects the D-ring.

The Gas-Dust "Atmosphere" of the Rings. The first indication of the existence of a rarefied gas-dust "atmosphere" of the rings was obtained in the 1936-1937 period by the Italian observer M. Maggini. In 1966, the Soviet astrophysicist, N. A. Kozyrev made an attempt to investigate this envelope spectroscopically. During the observations the Sun's rays were directed nearly along the plane of the rings and passed through the envelope by an extremely long path. This allowed one to hope that even with a slight absorption per unit of length of the envelope its spectral characteristics would be revealed sufficiently clearly. The aperture of the spectrograph was set up in a position parallel to the plane of the rings, and spectra were obtained of regions of the disk of Saturn in direct proximity to the rings, i.e., through the hypothesized envelope, and at a significant distance from them — at the point at which the envelope must terminate. The observations demonstrated that near the rings in the spectrum of the disk of Saturn, there was a weakening in the absorption of methane. Bands of ammonium, on the other hand, were stronger. A similar phenomenon must be observed in a case in which a region of the atmosphere of Saturn, illuminated by the Sun through an envelope, has a higher temperature than do regions illuminated directly by the Sun. Hence, it is in a similar manner that the envelope of the rings of Saturn is capable of creating a hot-house effect. Additionally, N. A. Kozyrev noted a strengthening of the lines of water vapor and a progress of spectral intensiveness with a long wave which is characteristic of ice crystals. He came to the conclusion that the gas-dust envelope of the rings of Saturn consists of small ice crystals and water vapor. The ice crystals can develop during collisions of the particles of the rings with each other (it is known that the particles are covered with a layer of snow or hoarfrost), and that molecules of H_2O are torn from the surface of the ice crystals by solar photons.



The Location of the Aperture of the Spectrograph on the Disk of Saturn During the Observations Made by N. A. Kozyrev on 10 through 21 October, 1966 (From the Left). 1, Disposition of the aperture in the region of the hypothesized gas-dust envelope of the ring; 2, 3, Outside the envelope. The shaded area indicates the shadow of the rings on the disk of the planet. From the right – profiles of the absorption bands of methane with a wavelength of 6,190 Å near the plane of the rings, where the atmosphere of Saturn is illuminated by the Sun through the envelope (points), and far from it (circles). Near the rings the absorption bands of methane are weaker.

The molecules of water vapor and the ice crystals, moving in the gravitational field of Saturn, must intersect the plane of the rings, and therefore the greater part of them quickly precipitate again on the surface of the /13 particles, of which the rings are composed. But it does not follow that one should add that both the molecules and the crystals collide with each other [Translator's note: the entire left margin of the copy is cut off, removing parts of words] these bows change their orbits. The occurrence of these random events can lead to a situation in which the trajectory of certain molecules and crystals will pass between the internal boundary of the rings and the orb of Saturn. Moving in this region, they will not collide with the substance of the rings, and therefore can exist for quite a long period of time. Consequently, one can expect that the basic cloud of gas and dust is located not above the plane of the rings, but rather between the internal boundary of the rings and the visible surface of the planet. This guess made by N. A. Kozyrev is confirmed by certain observed facts, which were noted at various times by other astronomers. Thus, as early as 1933 the Soviet planetary specialist N. P. Barabashov and B. Ye. Seleykin discovered that the space between the internal ring and the disk of the planet reflects blue rays, and, consequently, is filled with some sort of rarefied small, granular material (gas or dust). And at the end of 1969, the French astronomer P. Geren developed photographs containing weak traces of this cloud in yellow rays. The cloud has a circular shape and is separated from the crepe ring by a dark "space," similar to the well-known "space of Cassini" between the A and B rings.

Directly above the bright A- and B-rings there is no noticeable atmosphere. In order to be sure of this, the American scientists F. Franklin and A. Cook observed the spectra of Rhea, one of the satellites of Saturn, at moments in which rays of light, moving from this satellite to the Earth, nearly touched the plane of the rings. In the spectra of the satellites they did not find any traces of atmospheric absorption. Specifically, the concentration of sodium vapors in this space is known to be less than 100 atoms per cm^3 (for comparison one can recall that in 1 cm^3 of the Earth's atmosphere, in normal conditions, there are $2.69 \cdot 10^{19}$ molecules).

The Thickness of the Rings. The chief task of the "World-wide Saturn Watch" was the measurement of the thickness of the rings. One recalls that from the earlier observations it was only known that the thickness of the rings apparently is significantly less than 10 km, but the origin of this magnitude devolved from observational estimation, and for this the most varied values were suggested. Specifically, the American astronomer F. Franklin, in 1962, made the sensational statement that according to his "indirect" data the thickness of the rings of Saturn does not exceed 10 cm; the year 1966 put an end to these disputes.

How was the thickness of the rings successfully estimated? Suppose that one is observing Saturn through a telescope at the moment at which the Earth intersects the plane of its rings. One sees on both sides of the disk of the planet the two halves of the bright "needle," which the rings have been turned into. At a sufficiently large magnification one can see that the "needle" has, although it is small, a definite thickness. However, it would be incorrect to think that this is the actual thickness of the rings. This is their "seeming" or "visible" thickness which is caused by the widening of a reflection of any given heavenly body, which is common for a telescope, and which occurs /14 as the result of the wave properties of light and the turbulence of the terrestrial atmosphere. In the best conditions (high mountain observatory, exceptionally calm atmosphere) this widening comprises not less than 0.1 second of arc. But even ten km from the distance at which Saturn is located, they are seen at a angle of 0.0014 second of arc, while the actual thickness of the rings of Saturn is even less. Consequently, direct measurement of the thickness of the rings by their image in the telescope is impossible.

Photometry is of assistance here. It is not difficult to conceive of the fact that the brightness of the reflection of the rings will be as low as the intrinsic brightness of the edgewise reflection, since the actual thickness of the rings is less than their seeming thickness. Which of the magnitudes entering into this ratio are known? The seeming thickness and the brightness of the reflection can be measured. This pertains to the intrinsic brightness of the edgewise reflection, since during observations from the edgewise position of the rings the rings are opaque, while the reflective properties of the particles forming the rings, probably, are more or less identical throughout the entire volume of the rings, in which case one can expect that this magnitude is of an order of brightness of the side region of the rings in its most dense zones (the so-called B-ring). The brightness of the B-ring has been measured many times — it is approximately equal to the brightness of the center of Saturn's disk. Hence, of the four magnitudes three are known, which means that one can calculate the intrinsic thickness of the rings.

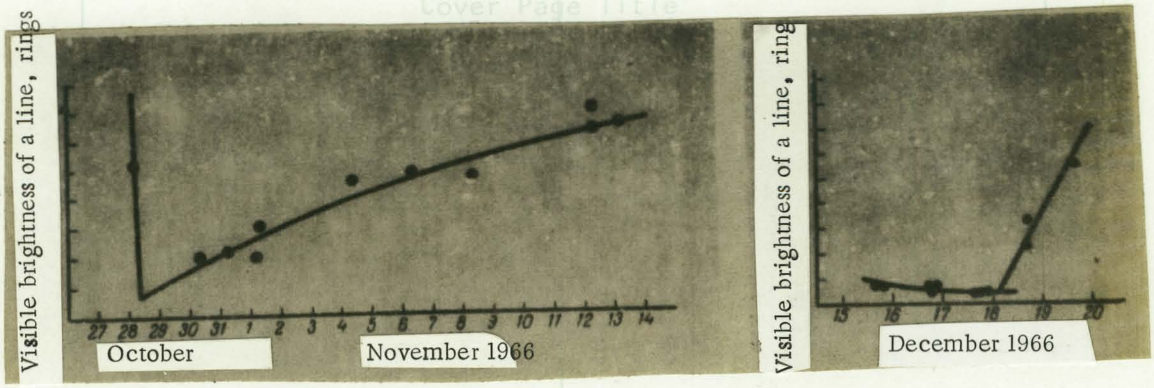
Factually, this business of measurement became more complex because in 1966 the observers were not successful in "catching" the exact moment in which the Earth passed through the plane of the rings, and therefore the light flux from the rings was not a flux only from the edgewise position; this flux was intermixed with the flux from the side region of the rings. The observers were forced to measure the brightness of the reflection of the rings several times at various apertures, and the moment of minimum brightness (interpolated) was accepted to be the moment of intersection of the Earth with the plane of the rings.

Observations made at the time of the October and December passages of the Earth through the plane of the rings were conducted by R. I. Kiladze in the USSR (the Abastumanskaya Observatory), by O. Dolfuss and G. Fokas in France (the Pic du Midi Observatory). R. I. Kiladze found a value of 1.5 km for the thickness of the rings in the blue rays, O. Dolfuss and G. Fokas found the value of 2.8 km in the yellow rays. Error in the estimations is estimated by the authors to be from 25 to 50%. Such were the first, pioneering estimates of the thickness of the rings of Saturn.

How the Particles of the Rings Move

Observed facts indicate that the diameter of a typical particle of the rings of Saturn is many times less than a kilometer. In other words, the dimensions of the particles are much less than the thickness of the rings. At the same time it is known from mechanics that the plane of the orbit of a satellite which rotates about the planet under the influence of the force of universal gravitation always passes through the center of a planet's mass. Doubtlessly, this also pertains to the particles of the rings of Saturn, each of which can /15
be viewed as a small satellite. How did the system of rings with a thickness of the order of several km form of such small particles? Obviously, the plane

of the orbits of the particles must be inclined at various slight angles to the median plane of the rings in such a way that all the planes have a single, common point coinciding with the center of Saturn's mass.



Change in the Visible Brightness of the Rings of Saturn Approximately at the Moments of the Passage of the Earth Through Their Plane in October and December of 1966. The minimum brightness corresponds to the moment of passage. Using the minimal brightness, for the first time a successful estimation of the thickness of the rings was made.

It would perhaps be clearer to represent this type of motion in the form of a sum of the circular orbital motion around Saturn in the median plane of the rings and of the fluctuations near the instantaneous disposition in orbit along three mutually perpendicular directions, of which two lie in the plane of the orbit, and the third is perpendicular to it.

One can demonstrate that if such a cloud of particles is not too transparent (and for the rings of Saturn this is in fact the case), then the particles will be constantly colliding with each other. But, as it is known, on impact part of the energy of the relative motion of the colliding bodies is converted into heat (disappears). In the case at hand the relative motion of the particles develops as a result of their fluctuations along three mutually perpendicular directions. Dissipation of this energy means a gradual dampening (a decrease of magnitude) of the fluctuations down to such a small value that the particles are no longer capable of colliding. In this instance their trajectories have been converted into nearly perfect circles, while the thickness of the rings will only slightly exceed the diameter of the particle.

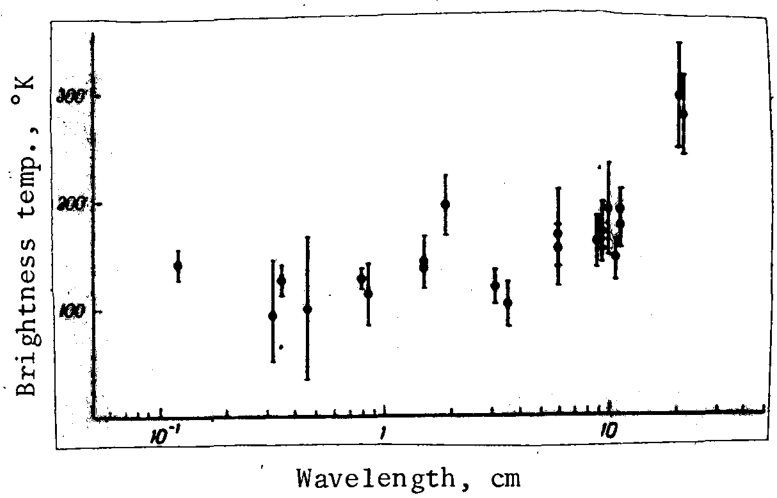
Since, however, the thickness of the rings is greater than the diameter of the particle by many times, the hypothesized picture does not correspond to reality. Moreover, for dampening of fluctuations an intermediate period of time is required which is extremely small in comparison with the time of existence of the solar system. Apparently, some sort of parallel process must occur which compensates for dampening of the fluctuations of particles and in the same manner maintains the thickness of the rings at a continuous level. In other words, a source of energy must exist which constantly makes up for the loss of energy as a result of dissipation. At present it is impossible to indicate this source with complete reliability. Doubtlessly, perturbation of the particles is caused by gravitational attraction on the part of the satellites, as well as the impacts of meteorites which constantly stir up the oscillating motion of the particles perpendicular to the medial plane of the rings and in this way constantly maintain a certain, more or less constant, thickness of the rings over the course of billions of years. However can these forces mentioned force these particles to the required levels of oscillation? The solution of this problem requires further research.

Saturn's Radio Emission

In what manner can one measure the flux of light which comes from Saturn to the objective of the optical telescope, how can one measure, as well, the flux of radio emission of this heavenly body, which is received by the antenna of the radio telescope. Knowing the area of the antenna, and the area of the heavenly body, one can calculate its "radio brightness" in that wavelength interval in which the receiving installation of the radio telescope works. One should recall that a heated body emits electromagnetic waves in an extremely wide range, including radio waves. Therefore, the radio brightness of a heavenly body can provide information concerning its temperature. One says "can," since there are other, nonthermal mechanisms of radio emission which are known. For example, a radio transmitter emits radio waves not as the result of the excess heat in the antenna, but rather due to is excitation of a rapidly alternating electrical current. Similar mechanisms also act in nature.

This small digression was made by the author in order that the reader would find it easier to understand the ideas of the graph which is represented on page 13, in which data of the results of measurement of the brightness of Saturn on various wavelengths of the radio range are presented. During the drawing of the graph it was hypothesized that the measured radio emission is thermal, and that therefore in place of brightness along the axis of the ordinate, one place the term "brightness temperature" — a magnitude representing the temperature of an ideal thermal emitter (an absolutely black body), the brightness of which, in the given interval of wavelength, would be equal to the measured brightness of the heavenly body. Additionally, it was proposed that the emissions being investigated by the radio astronomers be taken only from the visible disk of the planet, and therefore the slight possible radio emission of the rings of Saturn and its radiation belts are considered negligible. The accuracy of radio astronomical measurements is not yet so high that one can check the justification of this hypothesis; one can only say that it agrees with actual observational data. Specifically, according to the observations of the American radio astronomers, G. Berge and R. Reed, in the wavelengths of 9 and 10.7 cm, at least 90% of the radio emissions of Saturn originate in the visible disk of the planet, while the contribution of the radiation belts in the rings can comprise less than 10%. G. Berge and R. Reed came to the conclusion that in the centimeter wavelengths the overwhelming part of the radio emission of Saturn develops in its atmosphere. The recent observations of Saturn, carried out by the Soviet radio astronomers A. D. Kuz'min and B. Ya. Losovskiy demonstrated that the same was true as well for shortwave radio emis- /16 sions (0.8 cm).

The primary distinguishing feature of the graph under examination is the rise of the brightness temperature with an increase in wavelength. It is still early to introduce a formula which reflects the law of increase, because the contemporary accuracy of measurement is quite low, as a result of which the points being observed do not descend from the left to the right evenly, but rather "leap" in a disorderly fashion. However, it is possible that the jumps to some degree reflect the realistic characteristics of the progress of the temperature with wavelength; however, this can only be explained in the future, when the accuracy of measurements is successfully raised. However, one way or the other, the very fact of a rise in temperature with an increase in wavelength is not in question.



Brightness Temperature of Saturn in the Radio Range. The black lines correspond to errors in measurements. The accuracy of measurements are quite low, therefore the points "leap" in a disorderly manner. However, an increase in the brightness of temperature is noted with the growth of wavelength. In the infrared range (10 to 20 μ) the temperature of the planet is equal to 95 ± 3°.

This phenomenon can be explained by both thermal and nonthermal emission by the atmosphere of Saturn. The second hypothesis, at the present time, is extremely dubious. Actually, a force of nonthermal emission of the planet can be these or any other form of motion of charged particles, and also, particles in any sufficient number can be located either in the radiation belts, or in the ionosphere of the planet. If one is concerned with radiation belts, it should be borne in mind that the authors have already acquainted the readers with the intensity of the radiation belts' emissions, at any rate on the centimeter wavelengths, which are small and consequently it is improbable that the course of the temperature with any wavelength is related to them. With respect to the ionosphere, the theoretical calculations of the American scientist S. Galkiss, T. MacDonaff and H. Kraft (true, only for one concrete mechanism of emission) demonstrated that the required density of charged particles in it must be greater by one order of magnitude than in the ionosphere of Jupiter. It is difficult to admit that this is possible, since the basic source of ionization of particles in the atmospheres of both planets is solar radiation, the intensity of which at the distance of Jupiter is nearly 3 1/2 times greater than at the distance of Saturn.

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It is probably more correct to explain the increase of temperature with wavelength by thermal emission. One must bear in mind that the atmosphere of Saturn, as with the atmospheres of other giant planets, is very dense and opaque. Only emission from the thin, surface layer of the atmosphere can exit into interplanetary space; this layer of the atmosphere is transparent for the given wavelength. As a rule, the longer the wave, the greater the depth through which the registered emission passes. Hence, the observed growth of temperature with wavelength, most probably, reflects an increase in the temperature of the atmosphere of Saturn from deep within that atmosphere. Radio astronomical observations, apparently, make possible investigations of the atmosphere of giant planets to depths which are not reachable by optical telescopes. Of course, it would be desirable to conduct a deep sounding of the atmospheres of not only Saturn, but also of the closer planet, Jupiter; however powerful radio emissions of the radiation belts of the latter planet make this task practically insoluble.

Naturally, the question arises: why is it that Saturn, so similar to Jupiter, does not have such intense radiation belts? It is possible that here the "culprits" are the rings. The Soviet radio astronomer V. V. Zheleznyakov demonstrated that the matter of the rings, in its motion around Saturn, can attract the ionized gas of its radiation belts to itself, thereby attracting /17
along the plane of the rings the force lines of a magnetic field which is "frozen" to this gas. It is extremely probable that as a result there is a significant decrease in the concentration of particles in the radiation belts, and correspondingly, a decrease in the intensity of their radio emission.

To no less an extent, an answer is required to another question as well: why is the radio emission of the rings of Saturn so weak in comparison with the radio emission of the disk? Most simply this can be explained by the low temperature of the rings (40°K or less). However, according to the measurements of F. Low, the temperature of the rings reaches 84°K. In other words, the rings are not quite so "cold," but for some reason "poorly emit" in the radio range.

Is this possible? The capability of a body to emit one or another form of radiation in the spectral region (in this case in the cm waveband) is closely bound with its capability to absorb. If only a slight amount of the radiation striking the region is absorbed, (i.e., the body is comparatively transparent to the centimeter wavelengths of radio waves) then emission will also be slight. Many substances which are not transparent to ordinary light are to some degree transparent to radiowaves. The particles of the rings of Saturn are no exception; one knows that they are either stones, covered with a layer of hoarfrost, or are entirely made up of ice. As experiments show, the centimeter radio emission penetrates a stone monolith approximately 10 wavelengths, while it penetrates the depths of an ice coating to 100 wavelengths. If one takes into account that during the observations of A. D. Kuz'min and B. Ya. Losovskiy, the rings of Saturn were located in such a way that the line sight intersected only a few particles in all; then the rings of rock particles with a cross-section of 1 cm or of ice particles with a cross-section of 10 cm must be on the wavelength of 0.8 cm nearly entirely transparent, and could not provide any noticeable contribution to thermal radio emission of Saturn. It is perhaps in this that one can find the reason for the non-observability of the rings of Saturn by radio astronomers.

These new facts concerning the system of Saturn have been discovered by investigators in recent years. Scientists are not always agreed in their conclusions, but all the same these data significantly enrich our fund of knowledge concerning one of the most interesting of the giant planets.

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